Diffractive J/ψ production through color-octet mechanism in resolved photon processes at HERA

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Abstract

We use the color-octet mechanism combined with the two gluon exchange model for the diffractive J/ψ production in resolved photon processes. In the leading logarithmic approximation in QCD, we find that the diffractive J/ψ production cross section is related to the off-diagonal gluon density of the proton, the gluon density of the photon and to the nonperturbative color-octet matrix element of $\langle 0|\mathcal{O}_8^{J/\psi}[^3S_1]|0\rangle$. The cross section is found to be very sensitive to the gluon density of the photon. As a result, this process may provide a wide window for testing the two-gluon exchange model, studying the nature of hard diffractive factorization breaking and may be particularly useful in studying the gluon distribution of the photon. And it may also be a golden place to test the color-octet mechanism proposed by solving the $\psi'(J/\psi)$ surplus problem at the Tevatron.

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In high-energy strong interactions the Regge trajectory with a vacuum quantum number, the Pomeron, plays a particular and very important role in soft processes in hadron-hadron collisions [1]. However, the nature of the Pomeron and its interaction with hadrons remain a mystery. For a long time it had been understood that the dynamics of the " soft Pomeron " was deeply tied to confinement. However, it has been realized now that much can be learnt about hard diffractive processes from QCD, which are now under study experimentally. Of all these processes, the diffractive heavy quarkonium production has drawn specially attention, because their large masses provide a natural scale to guarantee the application of perturbative QCD. In Refs. [2,3], the diffractive J/ψ production cross sections have been formulated in direct photoproduction and deep inelastic scattering (DIS) processes in perturbative QCD. In the framework of perturbative QCD the Pomeron is assumed to be represented by a pair of gluons in the color-singlet state [4]. This two-gluon exchange model can successfully describe the experimental results from HERA [5]. An important feature of this perturbative QCD model prediction is that the cross section for the diffractive J/ψ production is expressed in terms of the square of the gluon density. In a previous paper [6], we extend the idea of perturbative QCD description of diffractive processes from ep colliders to hadron colliders, we give the formula for the diffractive J/ψ production at hadron colliders in the leading logarithmic approximation (LLA) in QCD by using the two-gluon exchange model. We introduce the color-octet mechanism to realize the color-octet $c\bar{c}$ pair evolving into J/ψ meson and show the importance of diffractive J/ψ production at hadron colliders to the study of small x physics, the property of diffractive process, the nature of the Pomeron and even for the test of color-octet production mechanism of heavy quarkonium. In this paper, we discuss another diffractive process, diffractive J/ψ production through color-octet machnism in resolved photon processes at HERA:

$$\gamma + P \rightarrow J/\psi + P + X. \tag{1}$$

This process is of special interesting because the produced J/ψ is easy to be detected through its leptonic decay modes and the diffractive J/ψ production rate is related to the off-diagonal gluon density in the proton and to the nonperturbative color-octet matrix element of J/ψ, furthermore, the rate is found to be very sensitive to the gluon density of the photon. The measurement of this process at HERA may provide a wide window for studying the nature of diffraction, and may be particularly useful in studying the gluon distribution of the photon. And it may also be a golden place to test the color-octet mechanism proposed by solving the $\psi'(J/\psi)$ surplus problem at the Tevatron.

In quantum field theory, the photon is the gauge boson mediating the electromagnetic interactions through the coupling to charged particles, in this respect, the photon appeares to be an elementary point-like particle. In other respect, the photon is subject to quantum fluctuation, it can fluctuate into a quark-antiquark pair ($q\bar{q}$) plus all other Fock states. If in photon-hadron interactions, the fluctuation time is large copared to the interaction time, the photon interacts with hadron through the interaction of these Fock states with hadron. This is the hadron-like nature of the photon which is well described by the vector dominance model (VDM) [7]. This dual nature of the photon have been studied in γP and $\gamma\gamma, \gamma^*\gamma$ scattering processes [8]. There are two basic types of inclusive processes where the partonic structure of the photon is investigated: one is the deep inelastiv scattering $e + \gamma \rightarrow e + X$ processes (DIS_γ), where the structure function of the photon $F_2^\gamma(x, Q^2)$ is measured [8,9].

the other is th large P_T jet and charged particle production in γP and $\gamma\gamma$ collisions, where individual parton densities in the photon are probed [8,10–12]. The measurements of the photon structure function $F_2^\gamma(x, Q^2)$ in DIS_γ are directly sensitive to the quark structure of the photon, however the presently available data on $F_2^\gamma(x, Q^2)$ are not precise enough to extracted the gluon distribution function of the photon through QCD evolution studies. First evidence for the gluon content of the photon was shown by KEK TRISTAN experiments through the study of two-photon production of large P_T jets [10]. Recently,, the Leading order (LO) gluon destribution of the photon in the fractional momentum rage $0.04 \leq x_\gamma \leq 1$ at the average factorization scales 75 and 38GeV^2 have been extracted by H1 Collaboration using dijet and large P_T charged particles photoproduction data [11]. More processes should be studied, in order to obtain more precise data to extracte the gluon content of the photon. We will see through the following study that diffractive J/ψ production in resolved photon processes at HERA can give valuable information about the gluon content of the photon.

Now, we discuss diffractive J/ψ production in resolved photon processes at HERA in two-gluon exchange model (Fig. 1). Within the nonrelativistic chromodynamics (NRQCD) framework [13,14] J/ψ is described in terms of Fock state decompositions as

$$
\begin{aligned}
|J/\psi\rangle = {} & O(1)\ |c\bar{c}[^3S_1^{(1)}]\rangle + O(v)|c\bar{c}[^3P_J^{(8)}]g\rangle \\
& + O(v^2)|c\bar{c}[^1S_0^{(8)}]g\rangle + O(v^2)|c\bar{c}[^3S_1^{(1,8)}]gg\rangle \\
& + O(v^2)|c\bar{c}[^3P_J^{(1,8)}]gg\rangle + \cdots,
\end{aligned}
\tag{2}
$$

where the $c\bar{c}$ pairs are indicated within the square brackets in spectroscopic notation. The pairs' color states are indicate by singlet (1) or octet (8) superscripts. The color octet $c\bar{c}$ states can make a transition into a physical J/ψ state by soft chromoelectric dipole ($E1$) transition(s) or chromomagnitic dipole ($M1$) transition(s)

$$
(c\bar{c})[^{2S+1}L_j^{(8)}] \to J/\psi.
\tag{3}
$$

The color-octet contributions are essential for cancelling the logarithmic infrared divergences which appear in the color-singlet model calculations of the production cross sections and annihilation decay rates for P-wave charmonia, and for solving the ψ' and direct J/ψ "surplus" problems at the Fermilab Tevatron [21,16]. The NRQCD factorization scheme [17] has been established to systematically separate these soft interactions from the hard interactions. In NRQCD, the long distance evolving process is described by the nonperturbative matrix elements of four-fermion operators and NRQCD power counting rules can be exploited to determine the dominant matrix elements in various processes [14]. For J/ψ production, the color-octet matrix elements, $\langle 0|\mathcal{O}_8^{J/\psi}[^3S_1]|0\rangle$, $\langle 0|\mathcal{O}_8^{J/\psi}[^1S_0]|0\rangle$ and $\langle 0|\mathcal{O}_8^{J/\psi}[^3P_J]|0\rangle$ are all scaling as $m_c^3 v_c^7$. So these color-octet contributions to J/ψ production must be included for consistency. But in diffractive J/ψ production, due to the nuture of vacuum quantum number exchange, the color-octet $^1S_0$ and ^3P_J subprocesses do not contribute to the diffractive J/ψ production. So the diffractive J/ψ production in resolved photon process in Fig. 1 can be realized via the color-octet $^3S_1$ channel only, in which the $c\bar{c}$ pair in a configuration of $^3S_1^{(8)}$ is produced in hard process as the incident gluon interacts with the proton by t channel color-singlet exchange (the two-gluon ladder parametrized Pomeron), and then evolve into the physical state J/ψ through emitting soft gluons which carry little momentum and will cause little change to the final state J/ψ spectrum in the diffractive processes.

For the diffractive subprocesses, $gp \to c\bar{c}[^3S_1^{(1)}]p$, the leading contribution comes from the diagrams shown in Fig.2. Due to the nuture of vacuum quantum number exchange, we know that the real part of the amplitude cancels out in the leading logarithmic approximation. The first two diagrams are similar to those calculated in direct photoproduction process, and the rest diagrams are new due to the existence of the gluon-gluon interaction vertex, those new diagrams are needed to guarantee the gauge invariance. For Fig.2(a), the imaginary part of the short distance amplitude $\mathcal{A}(g_a p \to (c\bar{c})_b[^3S_1^{(8)}]p)$, to leading logarithmic contribution, is [6]

$$\text{Im}\mathcal{A}^{(a)} = F \times \frac{1}{9}\delta^{ab}\frac{1}{s}(sg_{\mu\nu} - 2p_{2\mu}q_\nu - 2P_\mu^\psi p_{2\nu})\varepsilon_g^\mu \varepsilon_\psi^\nu \int \frac{dk_T^2}{k_T^4}\frac{1}{m_c^2}f(x', x''; k_T^2), \qquad (4)$$

where $F = \frac{3\pi}{2}g_s^3 m_c s$, a and b are the color indexes of the incident gluon and the $c\bar{c}$ pair in color-octet $^3S_1$ state. Factor $\frac{1}{9}$ is the color factor. p_2, q and P^ψ are the four-momenta of the proton, the gluon from the photon and the J/ψ respectivly, K_T is the transverse momentum of the gluon attached with the proton. $s = (q + p_2)^2$. ε_g^μ and ε_ψ^μ are the polarization vectors of the gluon from the photon and J/ψ. The function $f(x', x''; k_T^2)$ is related to the so-called off-diagonal gluon distribution function $G(x', x''; k_T^2)$ [18] by

$$f(x', x''; k_T^2) = \frac{\partial G(x', x''; k_T^2)}{\partial \ln k_T^2} \qquad (5)$$

Here, x' and x'' are the momentum fraction of the proton carried by the two gluons. In our calculations, we set the momentum transfer of the proton t equal to zero, i.e., $t = (k - k')^2 = 0$.

For Fig.2(b), the result is,

$$\text{Im}\mathcal{A}^{(b)} = -F \times (-\frac{1}{72}\delta^{ab})\frac{1}{s}(sg_{\mu\nu} - 2p_{2\mu}q_\nu - 2P_\mu^\psi p_{2\nu})\varepsilon_g^\mu \varepsilon_\psi^\nu \int \frac{dk_T^2}{k_T^4}\frac{1}{m_c^2 + k_T^2}f(x', x''; k_T^2), \quad (6)$$

where the color factor is $-\frac{1}{72}$. Unlike the case of the diffractive photoproduction processes, the color factors of these two diagrams (Fig.2(a) and Fig.2(b)) are not the same. The leading part of the contributions from these two diagrams (which is proportional to $\frac{1}{k_T^4}$) can not cancel out each other. After integrating the loop momentum k, for small k_T this will lead to a linear singularity, not a logarithmic singularity (proper in QCD) as that in diffractive direct photoproduction process [2]. So, there must be some other diagrams to cancel out the leading part of Fig.2(a) and Fig.2(b) to obtain the correct result. This is also due to the gauge invariance requirement. As mentioned above, in QCD due to the nonabelian $SU(3)$ gauge theory there are additional diagrams shown in Fig.2(c)-(e) as compared with that in direct photoproduction at ep colliders. By summing up all these diagrams together, we expect that in the final result the leading part singularity which is proportional to $\frac{1}{k_T^4}$ will be canceled out, and only the terms proportional to $\frac{1}{k_T^2}$ will be retained.

The contribution from Fig.2(c) is,

$$\text{Im}\mathcal{A}^{(c)} = 4F \times (-\frac{1}{8}\delta^{ab})\frac{1}{s}(sg_{\mu\nu} - 2p_{2\mu}q_\nu - 2P_\mu^\psi p_{2\nu})\varepsilon_g^\mu \varepsilon_\psi^\nu \int \frac{dk_T^2}{k_T^4}\frac{1}{4m_c^2 + k_T^2}f(x', x''; k_T^2), \quad (7)$$

where $-\frac{1}{8}$ is color factor. When we perform the integral over the loop momentum k, the main large logarithmic contribution comes from the region $\frac{1}{R_N^2} \ll k_T^2 \ll M_\psi^2$ (R_N is the nucleon radius) [2]. So, we calculate the amplitude as an expansion of k_T^2. From Eqs.(4), (6), (7), we can see that the leading part singularity from Fig.2(a)-(c) are canceled out as expected.

By the same reason, for Fig.2(d) and Fig.2(e), the leading part of each diagram is proportional to $\frac{1}{k_T^4}$. However, their sum is only proportional to $\frac{1}{k_T^2}$ because the leading part is canceled out. Their final results is,

$$\mathrm{Im}\mathcal{A}^{(d+e)} = F \times (-\frac{1}{2}\delta^{ab})\frac{1}{s}(sg_{\mu\nu} - 2p_{2\mu}q_\nu - 2P_\mu^\psi p_{2\nu})\varepsilon_g^\mu\varepsilon_\psi^\nu \int \frac{dk_T^2}{k_T^2}\frac{2}{16m_c^4}f(x', x''; k_T^2). \quad (8)$$

Adding all the contributions from Fig.2(a)-(e), we get the imaginary part of the short distance amplitude,

$$\mathrm{Im}\mathcal{A}(gp \to (c\bar{c})[^3S_1^{(8)}]p) = F \times (-\frac{13}{18}\delta^{ab})\frac{1}{s}(sg_{\mu\nu} - 2p_{2\mu}q_\nu - 2P_\mu^\psi p_{2\nu})\varepsilon_g^\mu\varepsilon_\psi^\nu$$
$$\times \int \frac{dk_T^2}{k_T^2}\frac{1}{M_\psi^4}f(x', x''; k_T^2). \quad (9)$$

Where $M_\psi = 2m_c$ are used. It is expected that for small x, there is no big difference between the off-diagonal and the usual diagonal gluon densities [19]. So, in the following calculations, we estimate the production rate by approximating the off-diagonal gluon density by the usual diagonal gluon density, $G(x', x''; Q^2) \approx xg(x, Q^2)$, where $x = M_\psi^2/s$. Finally, in the leading logarithmic approximation (LLA), we obtain the imaginary part of the short distance amplitude,

$$\mathrm{Im}\mathcal{A}(gp \to (c\bar{c})[^3S_1^{(8)}]p) = (-\frac{13}{18}\delta^{ab})\frac{F}{M_\psi^4}xg(x, \bar{Q}^2),\frac{1}{s}(sg_{\mu\nu} - 2p_{2\mu}q_\nu - 2P_\mu^\psi p_{2\nu})\varepsilon_g^\mu\varepsilon_\psi^\nu \quad (10)$$

Using Eq.(10), we get the cross section for the diffractive subprocess $gp \to J/\psi p$,

$$\frac{d\hat{\sigma}(gp \to J/\psi p)}{dt}\Big|_{t=0} = \frac{169\pi^4 m_c}{32 \times 27}\frac{\alpha_s(\bar{Q}^2)^3\langle 0|\mathcal{O}_8^{J/\psi}[^3S_1]|0\rangle}{M_\psi^8}[xg(x, \bar{Q}^2)]^2. \quad (11)$$

We have also calculated the color-octet $^1S_0$ and ^3P_J subprocesses. As expected they do not contribute to the diffractive J/ψ production. That is, only the color-octet $^3S_1$ contributes in this process. So the diffractive J/ψ production considered in this paper is sensitive to the matrix element $\langle 0|\mathcal{O}_8^{J/\psi}[^3S_1]|0\rangle$, which is very important to describe the prompt J/ψ production at the Tevatron. Therefore, the diffractive J/ψ production at hadron colliders would provide a golden place to test the color-octet mechanism in the heavy quarkonium production.

Provided the partonic cross section Eq.(11) above, we can get the cross section of diffractive J/ψ production in resolved photon processes. Assuming hard diffractive factorization, the differential cross section can be expressed as

4

$$\frac{d\sigma(\gamma + P \rightarrow J/\psi + P + X)}{dt}\Big|_{t=0} = \frac{169\pi^4 m_c}{32 \times 27} \frac{\alpha_s(\bar{Q}^2)^3 \langle 0|\mathcal{O}_8^{J/\psi}[^3S_1]|0\rangle}{M_\psi^8}$$

$$\times \int_{x_{1\min}}^1 dx_1 g(x_1, \bar{Q}^2)[xg(x, \bar{Q}^2)]^2, \qquad (12)$$

and

$$\sigma(\gamma + P \rightarrow J/\psi + P + X) = \frac{1}{b}\frac{d\sigma(\gamma + P \rightarrow J/\psi + P + X)}{dt}\Big|_{t=0} \qquad (13)$$

where b is the t slope of the J/ψ diffractive production in resolved photon processes, x_1 is the longitude momentum fraction of the photon carried by the incident gluon. So, the c.m. energy of the gluon-proton system is $s = x_1 S_{\gamma P}$, where $S_{\gamma P}$ is the total c.m. energy of the photon and proton system. Then, $x = M_\psi^2/s = M_\psi^2/(x_1 S_{\gamma P})$.

For numberical predictions, we use $m_c = 1.5$ GeV, $\Lambda_4 = 235$ MeV, and set the factoriztion scale and the renormalization scale both equal to the mass of J/ψ, i.e., $\bar{Q}^2 = M_\psi^2$. We assume the t slope b is the same as the value in the direct photoproduction of J/ψ process, i.e., $b = 4.5\text{GeV}^{-2}$ [5]. For the color-octet matrix elements $\langle 0|\mathcal{O}_8^{J/\psi}[^3S_1]|0\rangle$ we use the values determined by Beneke and Krämer [20] from fitting the direct J/ψ production data at the Tevatron [21] using GRV LO parton distribution functions [22]:

$$\langle 0|\mathcal{O}_8^{J/\psi}[^3S_1]|0\rangle = 1.12 \times 10^{-2} \text{ GeV}^3, \qquad (14)$$

As usual, in order to suppress the Reggon contributions, we set $x \leq 0.05$, so $x_{1\min} = 20M_\psi^2/S_{\gamma P}$.

In Fig. 3, we plot the total cross section $\sigma(\gamma + \text{p} \rightarrow J/\psi + \text{p} + X)$ as a function of the total c.m. energy of the photon and proton system Ecm(γp) in the range $160 \leq$ Ecm(γp) ≤ 250 GeV. We use the GRV LO gluon distribution function for the proton [22], and GRV LO, SaS2M, and WHIT1 parametrizations for the gluon distribution of the photon [23–25]. The solid curve is for GRV LO, dotted for WHIT1, dashed for SaS2M parametrizations for the gluon distribution of the photon. The results calculating from the GRV LO and WHIT1 gluon distribution sets are almost the same, while the cross section is larger for SaS2M set. In the Ecm(γp) range considered, the total cross section is in the region 0.24 nb $< \sigma(\gamma + \text{p} \rightarrow J/\psi + \text{p} + X) < 0.73$ nb. So this process can be studied at DESY HERA with present integrated luminosity. In Fig. 4, we plot the cross section $\sigma(\gamma + \text{p} \rightarrow J/\psi + \text{p} + X)$ as a function of the lower bound of x_1 in the integral of Eq.(12) at Ecm(γp) $= 200$ GeV using the GRV LO gluon distribution function for the photon and proton. From this figure, we see that the main contribution to the total cross section comes from the region $10^{-2} < x_1 < 5.0 \times 10^{-1}$, which contributes 89% of the total cross section. The region of $10^{-2} < x_1 < 5.0 \times 10^{-1}$ corresponds to the region $4.8 \times 10^{-3} < x < 2.4 \times 10^{-2}$ where the gluon desity of the proton is well determined by HERA experiments. So the measurement of diffractive J/ψ production in resolved photon process at HERA can determine the gluon desity of the photon in the region of $10^{-2} < x_1 < 5.0 \times 10^{-1}$.

In the above, we have assumed hard diffractive factorization in the resolved photon process. Recently, a factorization theorem has been proven by Collins [26] for the lepton induced hard diffractive scattering processes, such as diffractive deep inelastic scattering (DDIS) and diffractive direct photoproduction of jets. In contrast, no factorization theorem

has been established for hard diffraction in resolved photon processes and hadron-hadron collisions. At large $|t|$ (t is the square of the hadron's four-momentum transfer), where perturbative QCD applies to the Pomeron, it has been proven that there is a leading twist contribution which breaks the factorization theorem for hard diffraction in hadron-hadron collision [27]. This coherent hard diffraction was observed by the UA8 Collaboration in diffractive jet production, in this experiment t is in the region $-2 \leq t \leq -1$ GeV^2 [28]. In phenomenology, the large discrepancy between the theoretical prediction and the Tevatron date on the diffractive production of jets and weak bosons, *at al.*, signals a breakdown of hard diffractive factorization in hadron-hadron collisions [29]. Since in resolved photon processes, the photon behaves likes a hadron, we expect there are nonfactorization effects in diffractive resolved photon processes, but the nature of hard diffrative factorization breaking is unclear. Goulianos have concluded that the breakdown of hard diffractive factorization in hadron-hadron collisions is due to the breakdown of the Regge factorization already observed in soft diffraction [31] and this effects can indicated by the so-called renormalization factor D which takes the role of the survival probability for hadron emerges from the diffractive collision intact [30–32]:

$$D = \min(1, \frac{1}{N}), \tag{15}$$

with

$$N = \int_{\xi_{\min}}^{\xi_{\max}} d\xi \int_{-\infty}^{0} dt f_{\mathbb{P}/p}(\xi, t), \tag{16}$$

where $\xi_{\min} = M_0^2/Ecm$ with $M_0^2 = 1.5$GeV^2 (effective threshold) and $\xi_{\max} = 0.1$(coherence limit) and $f_{\mathbb{P}/p}(\xi, t)$ is the Pomeron flux factor. For our case, Ecm(γp) in the range $160 \leq$ Ecm(γp) ≤ 250 GeV, the renormalization factor D(Ecm)in the range $1/3 > D > 1/4$. The total cross section shown in Fig. 3 should multiplied by the renormalization factor D(Ecm) provided one takes into nonfactorization effects in this way. But the other results are unchanged. So the measurement of diffractive J/ψ production in resolved photon process at HERA can shed light on the nature of the hard diffractive factorization breaking.

In conclusion, in this paper We use the color-octet mechanism combined with the two gluon exchange model for the diffractive J/ψ production in resolved photon processes. In the leading logarithmic approximation in QCD, we find that the diffractive J/ψ production cross section is related to the off-diagonal gluon density in the proton, the gluon density of the photon and to the nonperturbative color-octet matrix element of J/ψ. The cross section is found to be very sensitive to the gluon density of the photon. Since the color-octet $^1S_0$ and ^3P_J subprocesses do not contribute to the diffractive J/ψ production, that is, only the color-octet $^3S_1$ contributes in this process. So the diffractive J/ψ production considered in this paper is sensitive to the matrix element $\langle 0|\mathcal{O}_8^{J/\psi}[^3S_1]|0\rangle$, which is well determined from the direct J/ψ production data at the Tevatron. Therefore, the diffractive J/ψ production in resolved photon processes would provide a golden place to test the color-octet mechanism in the heavy quarkonium production. Furthermore the measurement of diffractive J/ψ production in resolved photon process at HERA can shed light on the nature of the hard diffractive factorization breaking.

Acknowledgments

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Figure Captions

Fig.1. Sketch diagram for the diffractive J/ψ production in resolved photon processes in perturbative QCD. The black box represents the long distance process for color-octet $c\bar{c}$ pair in $^3S_1$ state evolving into J/ψ.

Fig.2. The lowest order perturbative QCD diagrams for the diffractive J/ψ production in resolved photon processes. The "$\times$" represents cutting the line.

Fig.3. The total cross section $\sigma(\gamma + \text{p} \rightarrow J/\psi + \text{p} + X)$ as a function of the total c.m. energy of the photon and proton system $\text{Ecm}(\gamma\text{p})$ in the range $160 \leq \text{Ecm}(\gamma\text{p}) \leq 250$ GeV. The solid curve is for GRV LO, dotted for WHIT1, dashed for SaS2M parametrizations for the gluon distribution of the photon.

Fig.4. The total cross section $\sigma(\gamma + \text{p} \rightarrow J/\psi + \text{p} + X)$ at the total c.m. energy of the photon and proton system $\text{Ecm}(\gamma\text{p}) = 200$ GeV as a function of the lower bound of x_1 in the integral of Eq.(12) using GRV LO parametrization for the gluon distribution of the photon.
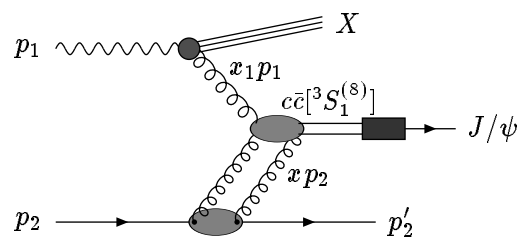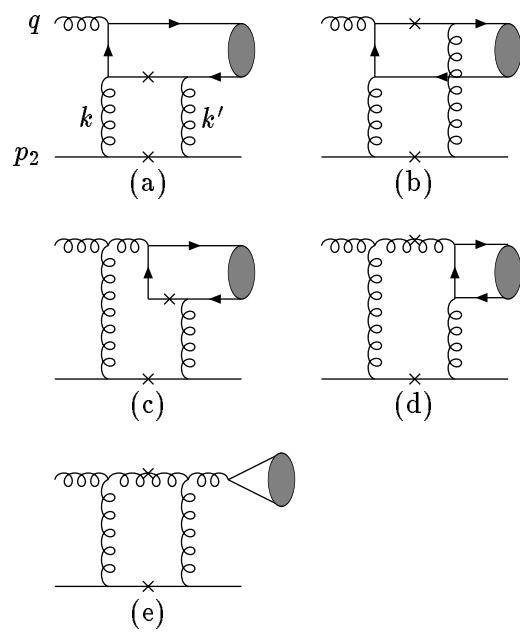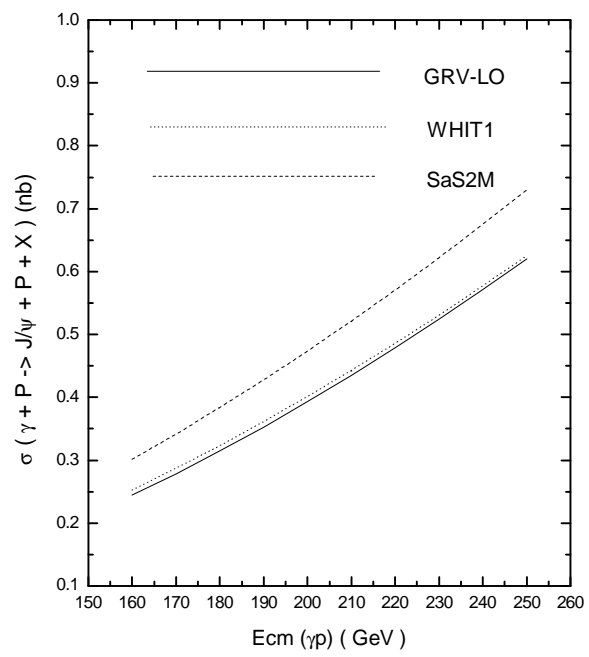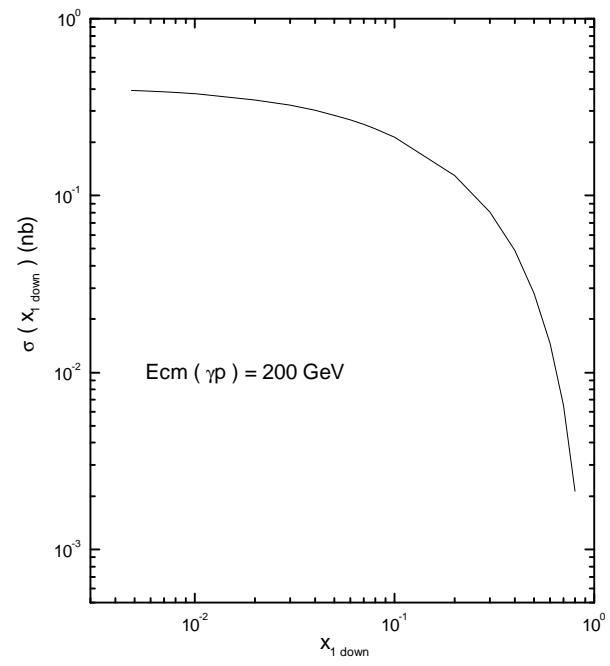
Fig.1

Fig.2

Fig. 3

Fig. 4